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Landschappen in 3D

3D-printen van hoge resolutie terreinmodellen met overlays van geologie en orthofoto's met ArcGIS en Blender

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Samenvatting

Bij de GIS-studio van de Faculteit der Natuurwetenschappen, Wiskunde en Informatica (FNWI) aan de Universiteit van Amsterdam, is een project afgerond waarin twee kaarten (modellen) zijn geproduceerd in 3D met behulp van ArcGIS, Blender en een 3D-printer. 3D-printen is een techniek in opkomst in zowel de wetenschap als in het bedrijfsleven, beeldende kunst en voor alledaagse objecten. Met de opkomst van LiDAR (Light Detection And Ranging), een relatief nieuwe remote sensing-techniek, worden steeds gedetailleerdere digitale hoogtemodellen gemaakt, waardoor het aardoppervlak in zeer hoog detail in 3D kan worden weergegeven. 3D-printen biedt hierop een uitstekende aanvulling, doordat het hiermee niet nodig is 3D data in 2D te visualiseren en analyseren, maar data direct in 3D kunnen worden bestudeerd. Een tutorial is ontwikkeld voor het maken van 3D-geprinte modellen vanuit digitale hoogtemodellen, welke als Engelstalige appendix is toegevoegd aan het eind van dit document.

Abstract

At the GIS-studio of the Faculty of Science (FNWI) at the University of Amsterdam, a project has been completed in which two maps (models) are produced in 3D using ArcGIS, Blender and a 3D printer. 3D printing is an emerging technology in both science and in business, fine arts and for everyday objects. With the advent of LiDAR (Light Detection And Ranging), a relatively new remote sensing technology, more and more detailed digital elevation models are being produced, displaying the Earth's surface in 3D in very high detail. 3D printing offers an excellent supplement, because with the use of it, it is not necessary to visualize and analyze 3D data in 2D, but the data can be studied directly in 3D. A tutorial has been developed for making 3D-printed models from digital height models, which is included as an English appendix at the end of this document.

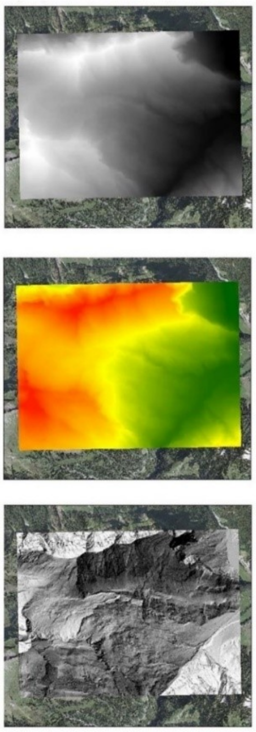
Zusammenfassung

Im GIS-Studio der Fakultät für Naturwissenschaften, Mathematik und Informatik (FNWI) der Universität Amsterdam wurde ein Projekt abgeschlossen, bei dem zwei Karten (Modelle) in 3D mit einem 3D-Drucker produziert wurden. 3D-Druck ist eine aufstrebende Technologie in Wissenschaft, Wirtschaft, bildender Kunst und für Alltagsgegenständen. Mit dem Aufkommen von LiDAR (Light Detection And Ranging), eine relativ neue Fernerkundungstechnologie, werden immer detailliertere digitale Höhenmodelle erstellt, die die Erdoberfläche sehr detailliert in 3D darstellen können. 3D-Druck bietet eine hervorragende Ergänzung dazu, da 3D-Daten in 2D nicht visualisiert und analysiert werden müssen, sondern Daten direkt in 3D untersucht werden können. Eine Anleitung (Tutorial) wurde entwickelt, um 3D-gedruckte Modelle aus digitalen Höhenmodelle zu erstellen, die als englischsprachiger Anhang (Appendix) am Ende dieses Dokuments enthalten ist.

3D-data

Driedimensionale representaties van het aardoppervlak, zoals digitale hoogtemodellen, zijn essentiële informatiebronnen voor vele disciplines van aardwetenschappen, planologie en industrie. LiDAR puntenwolken bestaan uit punten met een x-, y- en z-coördinaat, gemaakt op basis van laserpulsen, meestal vanuit een vliegtuig. Deze kunnen worden gebruikt om zeer gedetailleerde digitale hoogtemodellen te maken van een landschap. Door het gebruik van

laserpulsen kan het terreinoppervlak in detail worden gedetecteerd. Het bladerdek van eventuele begroeiing weerkaatst wel veel laserpulsen maar vaak dringen toch noch genoeg pulsen door het bladerdek om het terrein onder de begroeiing te kunnen reconstrueren. Dit stelt eindgebruikers in staat zowel het terrein als individuele gebouwen, bomen en struiken in detail te karteren. Afhankelijk van de gebruikte apparatuur en de topografie van het terrein, kunnen LiDAR puntenwolken een verschillend aantal reflectiepunten per vierkante meter hebben, wat de gebruiker in staat stelt door middel van interpolatie een digitaal hoogtemodel in rastervorm met verschillende resoluties te maken. Rasters van het Actueel Hoogtebestand Nederland (AHN) zijn bijvoorbeeld beschikbaar met een resolutie van 0,5 en 5 meter.
Er bestaat een groot verschil tussen processen aan het aardoppervlak, zoals die zich in de driedimensionale ruimte afspelen, en de manier waarop deze op een kaart in 2D worden gevisualiseerd. Digitale hoogtemodellen representeren 3D-data, maar worden in de regel in 2D gevisualiseerd, met een kleurcodering om de derde dimensie aan te geven. Dit brengt enkele inherente problemen met zich mee zoals contrast-effecten en verschillen in perceptie van mens tot mens. Hierdoor zijn gebruikers vaak niet daadwerkelijk in staat de derde dimensie accuraat te reconstrueren uit de kleurcodering. Het veelgebruikte regenboog-kleurenpalet (‘colormap’) bijvoorbeeld, ligt al enkele jaren ernstig onder vuur[1]. Daarnaast is het duidelijk dat het weergeven van 3D data in 2D met kleurcodering weinig nut heeft voor mensen met visuele beperkingen. Zoals te zien is in figuur 1a, linksboven, is het aflezen van hoogte van een 2D-afbeelding met kleurschaal (grijstinten in dit geval), niet even gemakkelijk interpreteerbaar en intuïtief als het interpreteren van een echt 3D-model. Verder laat fig. 1a ook een aantal andere conventionele 2D-kaarten met verschillende kleurcoderingen in ArcMap zien. Door de kleurcoderingen worden zulke kaarten ook wel met de term “2,5-D” aangeduid.
Figuur 1b gaat nog een stap verder door 3D-visualisaties in ArcScene, met het DTM als ‘base height’, waarop verscheidene andere rasters als ‘floating surface’ zijn afgebeeld, te tonen.



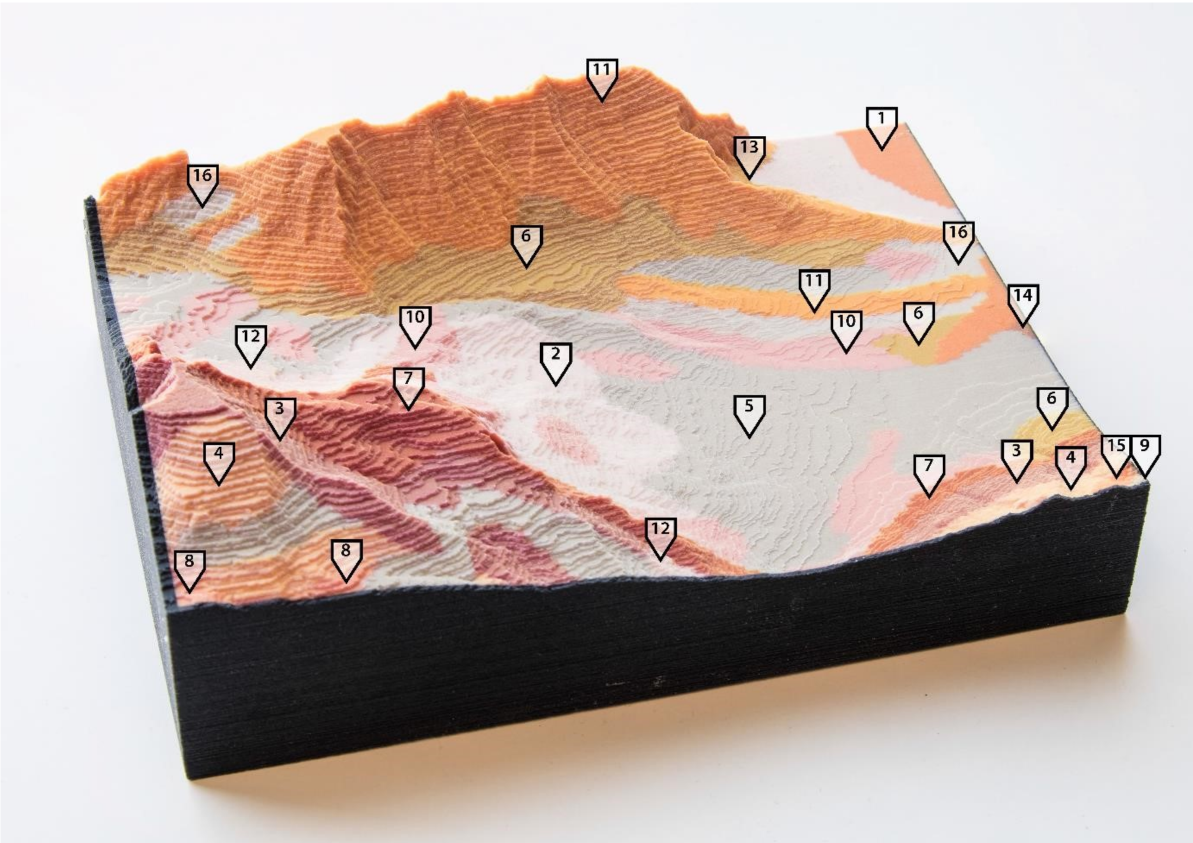
Figuur 1a) Conventionele 2D-kaarten in ArcMap met verscheidene kleurcoderingen (“2,5-D”): boven: grijstintenkaart, midden: rood-groen- kleurcodering, onder: hillshade-visualisatie.

Figuur 1b) 3D-visualisaties in ArcScene (“3D”): de DTM als 'base height', waarop verscheidene andere rasters als 'floating surface' zijn afgebeeld - boven: hoogtekaart met groen- rood-kleurcodering, midden: hillshade- visualisatie, onder: de kaart van geologische eenheden.

[1] Borland, D., & Taylor II, R. M. (2007). Rainbow color map (still) considered harmful. *IEEE computer graphics and applications*, (2), 14-17.

3D-printen

3D-printen kan een uitkomst bieden door een daadwerkelijke 3D-representatie vorm te geven. Hierdoor wordt 3D-printen in toenemende mate toegepast voor ontwerpen, voor het maken van schaalmodellen en zelfs binnen de medische wetenschap voor het maken van protheses. Met deze echte 3D-representatie en de hoge mate van detail die haalbaar is met 3D-printen, kan dit een geschikte techniek zijn om hoogtemodellen weer te geven in 3D. De GIS-studio van de Universiteit van Amsterdam (www.gis-studio.nl) heeft in samenwerking met masterstudente Earth Sciences Rúna Magnússon twee in 3D geprinte schaalmodellen van een door natuurgevaren bedreigd gebied in de Oostenrijkse Alpen gemaakt. De modellen zijn respectievelijk (l x b x h) 16,0 bij 12,0 bij 5,0 cm en 12,1 bij 13,1 bij 13,1 cm groot, en zijn gemaakt van gekleurd kunstmatig zandsteen met een cyanoacrylaatcoating. Dit is momenteel voor 3D-printers het enige materiaal waarin het opbouwen van kleurverschillen binnen zo'n model mogelijk is. De beide modellen zijn hol uitgevoerd om materiaal en kosten te besparen en de verzendkosten te minimaliseren. Het resultaat is te zien in figuur 2 en figuur 3.



Figuur 2) Foto van het 3D-geprinte hoogte-model van een gebied bij Au (Vorarlberg, Oostenrijk) met geologische eenheden als overlay, gemaakt door Jan van Arkel, UvA-IBED, 16-03-2016. Hier is te zien hoeveel gemakkelijker het is een beeld te krijgen van een terrein en relatieve hoogte daarbinnen met behulp van een 3D-geprint model. Verder is te zien dat een soort kunstmatige "terrassering" is opgetreden door limitaties in de resolutie van de 3D-printer. Daarnaast zijn enkele van de toppen (zie vooral linksonder) afgevlakt - dit is waarschijnlijk een fout in het printproces geweest. Afmetingen van het model: l x b x h: 16,0 x 12,0 x 5,0 cm.

LEGENDA

1 Aue längs der Flüsse
2 Bergsturzmasse, Blockwerk, z.T. in Massenbewegung mit Abrisskante
3 Drusberg-Formation (vom Freschen weg auskeilend)
4 Garschella-Formation ("Gault"); Seewen-Formation
5 Grund- und Endmoräne
6 Hang- und Bachschutt
7 Kieselkalk (im Kanisfluhgebiet unterlagernd Diphyoidesschichten)
8 Leimernmergel
9 Ofterschwang-Formation (in Vorarlberg "Basisserie")
10 Palfris-Formation (z.T. inkl. Zementstein-Schichten); Örfla- mit Betlis-Formation
11 Quinten-Formation
12 Rutschmasse bzw. Lockergestein in Massenbewegung mit Abrisskante
13 Schilt-Formation
14 Schwemmfächer und Murenkegel
15 Wildflysch i. Allg., (inkl. Junghansenschichten und Feuerstätter Sandstein)
16 Zementstein-Schichten

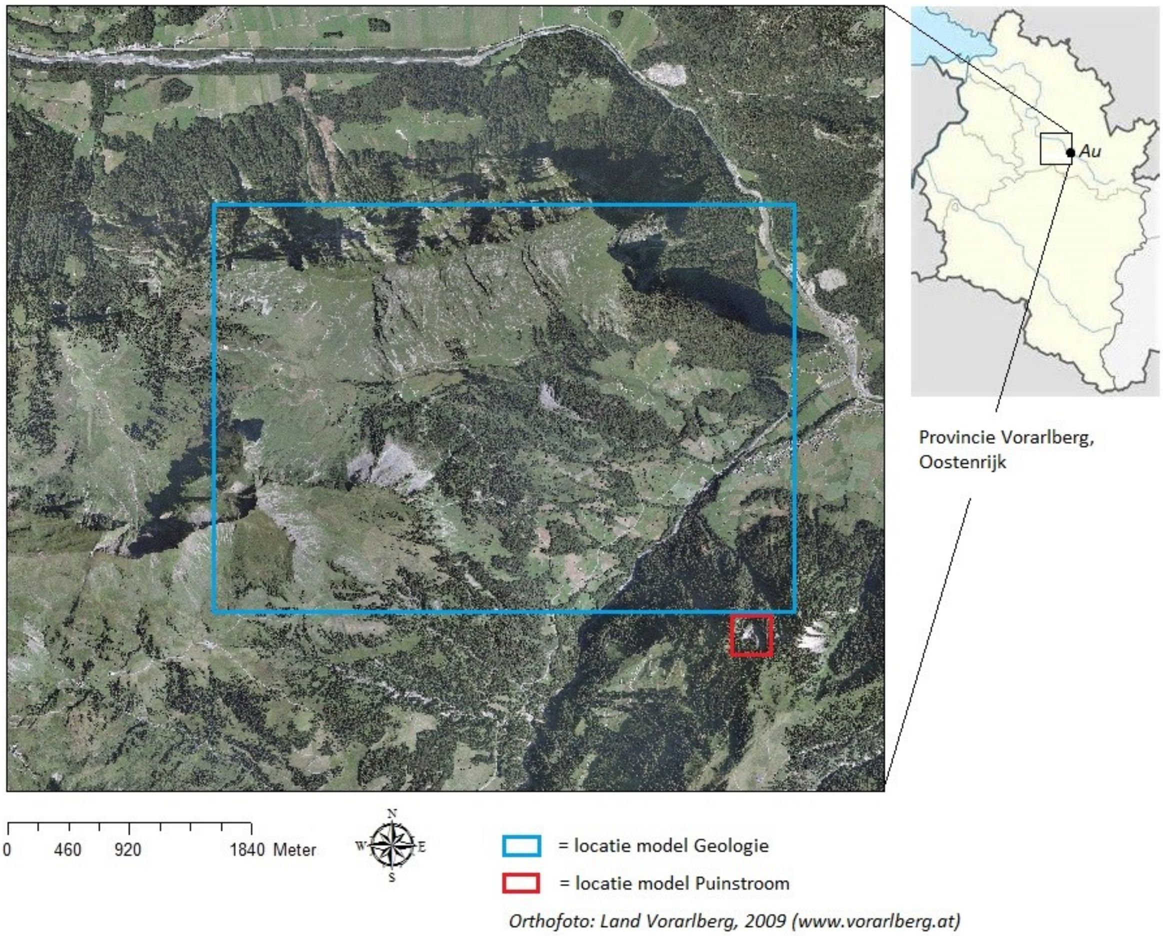
Figuur 3) Foto van het ge-3D-printe model van een puinstroom, ook nabij Au, met orthofoto als overlay. Hier is te zien hoe een kwaliteitsverlies is opgetreden van de hoge-resolutie orthofoto bij conversie van ArcMap naar Blender tijdens de UV-mapping-procedure. Afmetingen van het model: l x b x h: 12,1 x 13,1 x 13,1 cm. Foto gemaakt door Jan van Arkel, UvA-IBED, 16-03-2016.

3D-printen van hoogtemodellen

Het maken van 3D-hoogtemodellen vereist een omzetting van hoogtedata in rasterformaat naar een 3D-object dat is in te lezen door 3D-printersoftware, eventueel met een geassocieerd bestand van kleurspecificaties. Veelgebruikte bestandstypen voor dit soort 3D-modellen zijn .stl, .obj, en .x3d. Om van een hoogtemodel naar een 3D-model te komen dat printbaar en stevig genoeg is en dat de juiste kleurwaarden heeft, zijn enkele stappen nodig.

Voor deze modellen is dit gedaan door rasterdata in .tif-formaat om te zetten naar een 3D-bestand in .stl-formaat in het softwareprogramma MatLab, en vervolgens te bewerken in het open source 3D-modelleerprogramma Blender.

Het oorspronkelijke .tif-bestand is gemaakt door LiDAR-puntenwolken die beschikbaar zijn gesteld door het Land Vorarlberg[2] door middel van Mosaic Datasets in ArcMap 10 om te zetten in een .tif-raster. Hiervan zijn een groter gebied van 4 bij 4,5 km en een kleiner gebiedje van 230 bij 220 m geclipt. Het grotere gebied is een dal nabij het dorp Au in Vorarlberg, Oostenrijk, waarvan een geologische kaart (Geologische Bundesanstalt, 2007[3]) beschikbaar is. Het kleinere gebied toont een omvangrijke puinstroom (Engels: 'debris flow'), ook nabij Au, op een orthofotokaart uit 2009, ook beschikbaar gesteld door het Land Vorarlberg[4]. De locaties van beide modellen zijn afgebeeld in figuur 4.



Figuur 4) Kaart van de locaties van beide 3D-modellen; 'Model Geologie': zie figuur 2, 'Model Puinstroom': zie figuur 3.

Tijdens het ontwikkelen van de 3D-modellen moest rekening worden gehouden met zowel de resolutie van de LiDAR-dataset, als de kleinste printbare resolutie van de 3D-printer. Er is voor gekozen de modellen te laten printen door 3D-printbedrijf Shapeways[5], wiens Z-Corp 3D-printers een hoogste resolutie van 0,4 mm hebben voor details op het oppervlak van het model. Het model moest ook een minimale dikte (2 à 3 mm) hebben om niet te breken. Daarnaast is er beperkt ruimte binnen de 3D-printer waardoor geprinte modellen niet groter kunnen zijn dan 25 bij 38 cm, met een maximale hoogte van 20 cm.

[2] www.vorarlberg.at/
[3] www.geologie.ac.at/
[4] www.vorarlberg.at/
[5] www.shapeways.com

De LiDAR-datasets die zijn gebruikt voor de modellen hebben een gemiddelde puntdichtheid van 0,28 m voor terreinreflecties (‘ground returns’). Om grove interpolaties te voorkomen is hieruit met de Mosaic Dataset toolbox[6] in ArcMap 10.2.2 een digitaal terreinmodel (DTM) geïnterpoleerd met een resolutie van 1 bij 1 m. Omdat het DTM zo gedetailleerd is, en 3D-printers zulke fijne details kunnen printen, is het mogelijk om zelfs kleine landschappelijke elementen uit een digitaal hoogtemodel op hoge resolutie in 3D te printen. Echter, een 3D-model heeft een beperkt formaat, en voor schaalmodellen van grotere gebieden zal dus het uiteindelijke model minder detail vertonen dan theoretisch mogelijk is met de op LiDAR gebaseerde DTM. Voor de producten die ontwikkeld zijn voor de UvA GIS-studio is ervoor gekozen een print te maken van een groter gebied (het model met een overlay van geologische eenheden, het ‘Model Geologie’, zie fig. 2) en een model van een aardwetenschappelijk interessant fenomeen in detail (het ‘Model Puinstroom’, zie fig. 3).

Eindproducten

De eindproducten zijn - meteen bij de eerste poging - beide geheel intact uit de 3D-printer gekomen. Het verwerken van de modellen door 3D-printbedrijf Shapeways nam, inclusief verzending van de modellen vanuit Amerika, 17 dagen in beslag. De enige kleine complicaties waren dat in het geologische model de topjes van de bergruggen hier en daar afgevlakt waren, omdat deze anders te fragiel zouden zijn geworden om te 3D-printen. Ook is er in het geologische model een aantal kleine kleurverschillen opgetreden, wat te wijten is aan het zeer hoge detail in reliëf in dit model. De modellen zullen worden gebruikt als demonstratiemateriaal voor de GIS-studio en kunnen worden ingezet als ondersteunend materiaal tijdens lezingen, cursussen en veldwerk. Daarnaast is een tutorial ontwikkeld voor het maken van 3D-geprinte modellen vanuit digitale hoogtemodellen, welke als Engelstalige appendix is toegevoegd aan het eind van dit document.

Nieuwe ontwikkelingen

Het 3D-printen van landschappen is tot dusver beperkt tot het maken van schaalmodellen voor hobbyisten. Wij voorzien een belangrijke rol voor 3D-printen in het bestuderen van allerlei - al dan niet aardwetenschappelijke - fenomenen in een tastbare driedimensionale setting.

3D-printen kan worden gebruikt om demonstratiemodellen te maken van wetenschappelijke testopstellingen, schaalmodellen van nieuw te ontwikkelen producten, voor het maken van maquettes, enzovoort. Verdere voordelen van 3D-visualisaties (t.o.v. 2D-afbeeldingen) zijn het interpreteren van moeilijk bereikbare terreinen en het visualiseren van land cover scenario’s op het terrein. Ook hebben geprinte 3D-modellen duidelijke voordelen t.o.v. bijvoorbeeld digitale 3D-modellen in ArcScene: je kunt de modellen meenemen naar plaatsen waar je geen IT-voorzieningen hebt, je kunt ze rond laten gaan in een (college-)zaal, en ze zijn tastbaar, wat in het voordeel werkt van mensen met een visuele beperking. Specifiek binnen de aardwetenschappen kan het, zoals hier gedemonstreerd, worden toegepast om modellen te maken van landschappen en processen aan het aardoppervlak.

[6] http://desktop.arcgis.com/en/arcmap/10.3/manage-data/raster-and-images/what-is-a-mosaic-dataset.htm

Dit kan in steeds meer detail naarmate gedetailleerdere hoogtemodellen in 3D kunnen worden geprint met technieken als LiDAR. Esri Nederland kan een bijdrage leveren aan deze ontwikkelingen door het aanbieden van een mogelijkheid tot conversie naar de meest gebruikte 3D-bestandsextensies (zoals .stl, .obj en .x3d) in de ArcGIS-suite. Het zou best kunnen dat 3D in de toekomst de norm wordt. Zo zijn er al ontwikkelingen gaande op het gebied van 3D-monitors.

Trefwoorden: 3D, 3D-printen, 3D-model, LiDAR, DEM, ArcGIS, Blender, Vorarlberg, geologie, orthofoto.

Keywords: 3D, 3D-printing, 3D-model, LiDAR, DEM, ArcGIS, Blender, Vorarlberg, geology, orthophoto.

Stichwörter: 3D, 3D-Drucken, 3D-Modell, LiDAR, Laserscannerdaten, DGM, ArcGIS, Blender, Vorarlberg, Geologie, Orthophoto.

Appendix

3D-printing landscape models from LiDAR data

A tutorial by Rúna Magnússon, Institute of Biodiversity and Ecosystem Dynamics,

University of Amsterdam

28/04/2016

Supporting material for:

Magnússon, R. Í., de Boer, W. M. & Seijmonsbergen, A. C. (2016): Landschappen in 3D. - 3D-printen van hoge resolutie terreinmodellen met overlays van geologie en orthofoto's met ArcGIS en Blender.

http://magazine.esri.nl/esri-magazine#!/3d-innovaties/item/0

Contents of the publication and the Appendix

Introduction

Three-dimensional representations of Earth's surface such as Digital Elevation Models are essential in various disciplines ranging from geophysical sciences to spatial planning and industry (Sulebak, 2000). LiDAR point clouds can yield highly detailed digital elevation models, enabling the detection of features such as individual trees and sub-canopy terrain. Depending on the data acquisition process, point clouds can have a variable number of return points per square meter, which enables the interpolation of DTM's and DSM's of very increasingly resolution. Resolutions of 0.5 m are not uncommon (van der Zon, 2013; Bater & Coops, 2009).

Digital elevation models represent 3D data, but are generally displayed in 2D map projections with color maps representing the third dimension, or the y rely on intensive 3D video animation techniques such as fly-through (Sulebak, 2000). Using color as a quantitative variable to represent height however, comes with inherent problems related to color perception such as color shift effects (Tufte, 1991). It is also evident that these representation may be problematic for users with some visual handicap or little experience with computers. And in general a large gap remains between the 3D nature of the Earth's surface and its processes and the way it is represented in 2D or in perspective views (Sulebak, 2000).

3D printing can provide a true 3D representation of the Earth's surface, or any object. This has made that 3D printing is growing rapidly as a technique in engineering, but also in medicinal sciences for the development of 3D models or organs and tissues or even actual prostheses (Schubert et al., 2013). Given its true 3D representation abilities and high detail (up to under a millimeter) (Shapeways, 2015) 3D models generated from LiDAR derived DEM's may be of high value in Earth Science applications.

This tutorial provides a workflow to generate a 3D model of a surface interpolated from LiDAR data of the Au region in the province of Vorarlberg, Austria. These models can be used for demonstration purposes and may aid learning by providing a true 3D representation. In order to ensure maximum feasibility and reproducibility, a combination of widely used software in Earth Sciences and open source 3D modelling software will be used. Moreover, this tutorial will provide ways of ensuring affordability of the scale models by optimizing data density compared to material volume. Lastly, techniques to overlay a raster image onto the 3D object representing an extra data dimension, such as an orthophoto, geological map or topographical map will be provided.

Tutorial

This tutorial uses several .las files of the Au region in Vorarlberg, Austria, which are provided with the tutorial, together with a geological map and orthophotos of the area (see Addendum). These data, downloaded from the UvA Geoportal[7] are provided as an example but you will be free to choose which data and which exact location you will use for this tutorial. For following this tutorial it is required to have access to ArcGIS (or an equivalent GIS environment), LAStools, MatLab and Blender. All these programs are available at the UvA GIS-studio (www.gis-studio.nl). Blender can be downloaded for free[8]. First, you will prepare the LiDAR data and image overlays in ArcGIS and in LAStools. Then, you will use MatLab to convert the DEM to a basic 3D model. Lastly, Blender will be used to edit the 3D model in order to make it printable. The workflow is outlined in fig. 1.

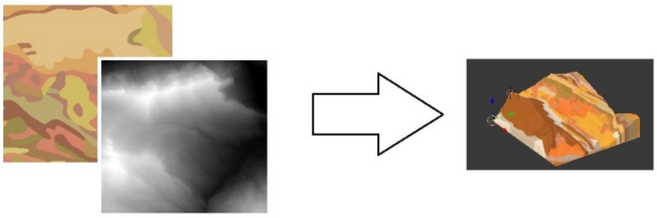


Figure 1) From a digital elevation model (DEM) and an additional raster containing for instance orthophoto, geomorphological or geological data (left side), a coloured 3D model will be created (right side).

Part I: Preparing the LiDAR & raster data in ArcGIS

→ Connect ArcCatalog to the folder containing your image layer and the .laz files. In the folder, create a file geodatabase to store the image layer and set its projected coordinate system. In case of the example dataset of Vorarlberg, set it to *UTM > Europe > ETRS 1989 UTM Zone 32N.*

→ Open ArcMap. Connect to the folder containing your file geodatabase and the folder containing LAStools. First, use the laszip function from LAStools to unzip the .laz files to .las files.

→ Use the "Point file information" tool to get an idea of the properties of the las files you're using. It will tell you the amount of points, point classes, average point spacing and statistics (fig. 2). Make sure to select "summarize by class code" in the tool interface.

7 http://geodata.science.uva.nl:8080/geoportal/catalog/main/home.page

8 www.blender.org and http://rapidlasso.com/lastools/

FID	Shape *	FileName	Class	Pt Count	Pt Spacing	Z Min	Z Max
0	Polygon	13255000.las	0	19621	17,844907	622,29	1992,17
1	Polygon	13255000.las	1	20993	15,222325	692,67	1343,32
2	Polygon	13255000.las	2	76653038	0,285544	691,21	1614,7
3	Polygon	13255000.las	3	16277384	0,619649	691,39	1617,2
4	Polygon	13255000.las	4	15351296	0,638066	696,12	1618,03
5	Polygon	13255000.las	5	69606720	0,299649	708,36	1617,98
6	Polygon	13255000.las	6	1017769	2,271978	694,19	1315,39
7	Polygon	13255000.las	7	1968	37,005301	694,43	987,93
8	Polygon	13255000.las	8	56356	9,928443	696,52	1402,38
9	Polygon	13255000.las	9	137240	6,246867	697,02	1179,93
10	Polygon	13255000.las	10	8272	16,59948	700,33	944,89
11	Polygon	13255000.las	15	3633	26,128117	717,26	1033,04
12	Polygon	13255000.las	16	3818	25,277837	712,89	1034,28
13	Polygon	13255002.las	0	5918	32,483654	565,77	1633,47
14	Polygon	13255002.las	1	70163	8,522403	692,36	1143,57
15	Polygon	13255002.las	2	84703155	0,271637	677,53	1429,97
16	Polygon	13255002.las	3	14697296	0,652108	677,87	1432,34
17	Polygon	13255002.las	4	15949939	0,625978	680,78	1439,28
18	Polygon	13255002.las	5	94680722	0,256926	687,89	1450,21
19	Polygon	13255002.las	6	731595	2,843373	685,18	1432,98
20	Polygon	13255002.las	7	789	81,742082	664,81	1422,63
21	Polygon	13255002.las	8	80194	8,787819	683,95	1434,84
22	Polygon	13255002.las	9	148821	5,040267	677,51	746,75
23	Polygon	13255002.las	10	36711	11,11788	678,55	1108,32
24	Polygon	13255002.las	15	13890	17,66794	696,33	1433,84
25	Polygon	13255002.las	16	6656	25,295753	699,38	1435,2

Figure 2) Example of the attribute table of the point file information files of several .las files.

The .las files have an average point spacing of 0.2 meters overall, and an average point spacing of around 0.28 meters for ground points (class 2 is ground by convention).

→ Create a mosaic dataset within your file geodatabase by right clicking the file geodatabase. Give it a name and select UTM > Europe > ETRS 1989 UTM Zone 32N as the projected coordinate system. In the catalog window, right click the mosaic dataset and click add rasters. This opens the interface shown in figure 3.

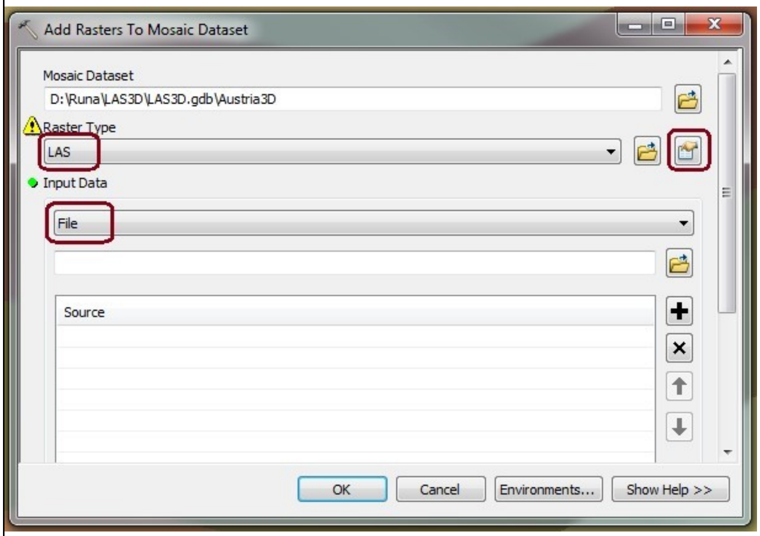


Figure 3) Add rasters interface in ArcGIS.

Change file input type from workspace to file and select the .las files you are using.

Set raster type to LAS and select the edit icon on the right of the raster type selection dropdown menu. This opens the interface as shown in figure 4.

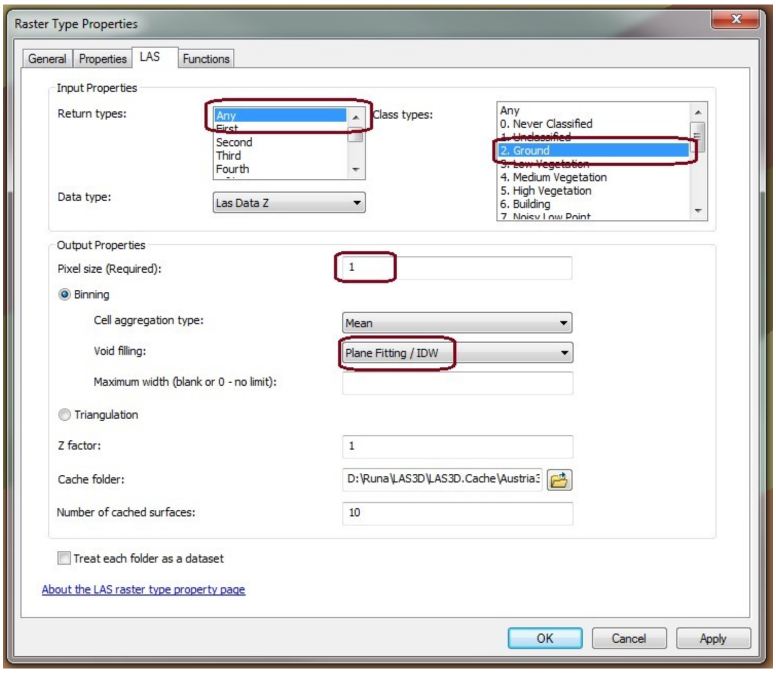


Figure 4) LAS settings interface.

Under the LAS tab, select "last" for return type and class type ground.

Enter pixel size 1 x 1 m for now. You can decide to choose another resolution, depending on the size of your area of interest and your computer's capabilities.

Click OK. Do not panic if the DEM is not visible right away.

DEM pixel size is an important consideration; generating grid DEMs from LiDAR datasets requires the choice of a grid cell size. There is no universal rule to determine the optimal cell size, but it should be chosen in such a way that it represents the variability of the surface and features in the terrain (Liu, 2008). A rule of thumb could be to use 3 to 4 times the average point spacing as pixel size, which generally ensures that all voids that may exist between data points are filled (ESRI ArcGIS Resources, 2014), or to pick a number of grid cells that is roughly equal to the number of points in the .las file (Liu, 2008).

3D printers have limitations in the amount of detail they can print. Depending on the material you print in, details of up to 0.1 millimeters can be printed (Shapeways, 2015). But you will also need to choose an extent that allows you to see sufficient features and variations in your model.

***Example:** Assuming that we will print an area of 200 x 200 meters, we can set the resolution of our grid to 1 x 1 m, and tell the printer that we are using millimeters as input unit. This will result in a 20 x 20 cm model which is within the maximum printing size of conventional 3D printers. It will have a printed resolution of 1 mm, which for most 3D printers is still on the coarse side!*

You have now interpolated a DEM from the LiDAR data using mosaic datasets.

→ Right click the image layer of the mosaic dataset in the TOC (Table Of Content) and select “export data”. Set output type to TIFF and set the X and Y cell size to your desired resolution. Clip this .tif file to your area of interest.

Note: if you pick a very small area of interest, for instance 10 x 10 m, you will only have a small amount of grid cells and you will either get a very coarse and big 3D printed model, or a very fine but very small model! The larger the model, the more material and the more expensive. The smaller the model, the less space for surface features. Also relate this to the image layer you are using; is it a very detailed one or a very coarse one?

→ Also clip the image layer to the area of interest to a TIFF file and leave the X and Y cell size as default. Export the image layer (for instance the geological map or orthophoto) of the area of interest to .png for later use. (Right click data layer in the TOC, click export data). Make sure to select “use renderer”, “force RGB” and “use color map” if you want to keep the current symbology!

You have now created DEMs and additional raster data to use for your 3D model. You can create a preview of the 3D model in ArcScene if you want by adding the image layer to the map and setting your DEM as base height.

Part II : Using MatLab to convert to .stl and support structures.

The .tif file representing the AOI (Area Of Interest) now has to be converted to a 3D plane interpretable by 3D modelling software. A script is provided to achieve these goals, called *CreateMesh.m*. The script in turn loads the elevation data from the tiff, fills NoData values, smooths the DEM and writes it to .stl.

First, it loads the .tif DEM, and replaces ArcGIS NoData-values with NaN’s. It smooths the DEM to a small extent, ensuring that no too sharp features are present on the surface. These will probably occur as a result of the very fine spatial resolution of the LiDAR DEM, but in the printing process they will break inevitably.

The script also ensures that the model is provided with walls to the sides to ensure that it can stand upright properly. This is done by making sure that after the filtering, the edges of the model are set to 0. For the rest, the model will remain hollow, to reduce printing costs.

The DEM will then be written to a .stl file using the stlwrite() function from the MatLab Central File Exchange[9]. stl, or Standard Tessellation Language, which is the most widely used file format for 3D printing[4].

9 http://www.mathworks.com/matlabcentral/fileexchange/20922-stlwrite-filename--varargin- [4] http://en.wikipedia.org/wiki/STL_%28file_format%29

→ Open the script CreateMesh.m and enter the name of your .tif DEM file and the desired output location for your .stl file. Run the script.

In theory, we could already print this model. However, the wall thickness will not be sufficient yet, and the model will most likely need to be rescaled. 3D printing services such as Shapeways and 3D Hubs require that units of the model are specified as mm, cm or even meters. If our original DEM had a 0.5 m resolution and we map an area of 500 x 500 meters, this would result in a 1000 x 1000 plane, and either a 100 x 100 cm, 10 x 10 m or 1000 x 1000 m large scale model. Most 3D printers however are capable of printing only about 20 x 20 cm (Protospace, 2015) to 20 x 25 cm (Shapeways, 2015).

Two strategies are possible; subdivide the grid and print make 25 miniature models, and adapt the supporting structures of each model so that all the 25 models connect and can be turned into a large 1 x 1 m scale model (you can imagine how expensive this would be), or simply scale down the model.

The open source 3D modelling software Blender offers many options such as scaling a 3D model, adding a color layer and adding a specified thickness. Moreover, it allows you to view the 3D object created from all angles while adapting it. Blender is a complicated program, but the next section will guide you through all the necessary steps to make the 3D model ready for printing and adding color to the top surface.

Part III: 3D modelling in Blender

The .stl file created in MatLab can be imported into Blender directly. Download Blender 2.7 and open it[10]. By default, Blender will display a box. You won't use it here. Right click it > press x > press enter to delete it.

→ Open the .stl model. Click *File* > *Import* > *.stl* and browse to your file created from the MatLab script.

The file should open as a 3D plane. To zoom in on it, right click it and press the . / delete button on the numpad on the right side of your keyboard. You can now turn it by using the numbers on the numpad, play around to get familiar with it.

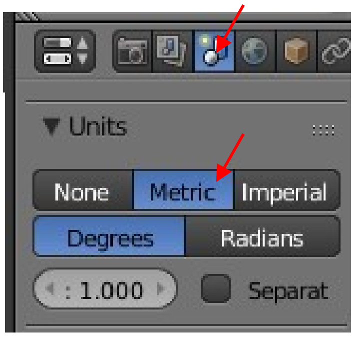


Figure 5) Set Blender units to metric units

10 www.blender.org

We will scale the model to such a size that it is printable by a 3D printer.

By default, Blender uses "Blender Units", but we will set it to metric.

→ In the right-hand toolbar, browse to Scene (fig. 5).

→ Under Units, select Metric and Degrees (fig. 5).

When we print the model we will instruct the printer to interpret units as millimeters, so we can now pretend that the "meters" in our model will be millimeters eventually.

We need to scale the model to fit into the minimum "bounding box" of the printer. This minimum and maximum bounding box are determined by the interior space in a 3D printer. It is usually not much more than 20 or 25 cm in X and Y dimension or 38 cm in Z dimension. We need to take this into account when we develop a product.

Here, we will scale in such a way that the model will become something like 20 x 20 centimeters; so in Blender the model will need to be around 200 x 200 meters (which will later become 200 x 200 mm). It is also possible to add a vertical exaggeration if desired.

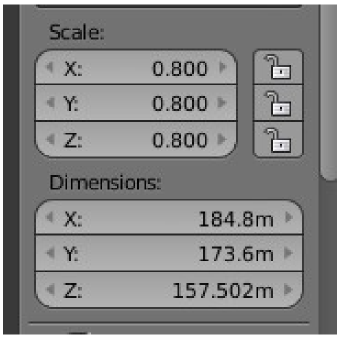


Figure 6) Transformation toolbar (left)

Figure 7) Scaling options (right)

→ Click the small + to the left of the right hand options panel to make the transform menu appear (fig. 6).

→ Under "scale", add a ratio for the X, Y and Z that makes sure that the dimensions in all directions fit within the printer (fig. 7).

We now have a plane of the right dimensions, but our model has no thickness and thus it cannot be printed. When adding model thickness, it is important to know which material we will be printing in, since each material has different strength and flexibility properties. Refer to the Shapeways Materials Guide[11], and check the minimum unsupported wall thickness of Sandstone Material. To add a thickness, we need to add a "modifier" to our object. Modifiers are operations that you can perform on your object. They do not alter the object geometry, but only affect the way the object is rendered and displayed eventually[12]. So the original .stl model is not in any way affected, but the rendered object will get a thickness. This object we will later save as a new object.

11 http://www.shapeways.com/materials/full-color-sandstone?li=nav

12 https://www.blender.org/manual/modifiers/index.html

Figure 8) Modifiers toolbar

→ From Scene, switch to Modifiers (fig. 8, enlarge the toolbar if this icon is not visible).

→ Click Add Modifier and select “Solidify”.

This will give all walls in the model a preset thickness (fig. 9), which is very convenient for 3D printing purposes. Remember that every meter corresponds to a millimeter, and that we will want something about 3 mm thickness at least. Add 3 mm thickness by adding 3 meters of thickness in the solidify tool. Before clicking apply, check in the object window whether it looks good and solid to you.

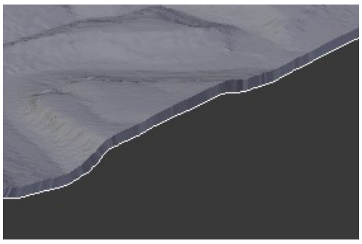


Figure 9) The 3D model’s wall after adding thickness

→ Examine the thickness and size of your model (fig. 9) – if you’re confident about it, save it as a new .stl file using: *File > Export > .stl*

Part IV: Intermezzo: Check your model's printability

The model can now be printed. But we will need to check whether all the criteria for a reliable and working print are met. The main criteria are summarized in table 1.

Table 1) Summary of main criteria for successful 3D prints[13].

Criterion	Explanation
Bounding box	The model is small enough to fit into the printer's interior and large enough to be worth printing.
Wall thickness	The walls in the model are thick enough to stay intact during printing, polishing and transport.
Wire thickness	Wires are thin elements in the 3D model (the length is at least twice the width) that may break during printing, finishing or transport.
Minimum engraved detail	This is the minimum size of a feature that will still be printed, which is determined by the 3D printer's resolution.
Presence and size of escape holes	If your model contains closed hollow features, you will need to create "escape holes" to allow the printer's powder material to be taken out.
Clearance between multiple parts	The minimum space present between non-connecting parts of the model.

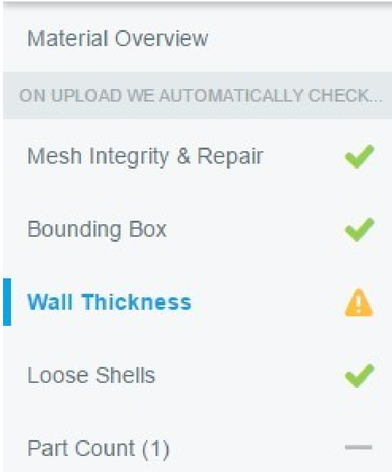
There are several services online to check the printability of your model, among which are Netfabb.com, minimagics.com and shapeways.com. Shapeways is very user friendly and the process of checking your model is outlined below.

→ Go to shapeways.com and create a free account (you may receive newsletters from Shapeways). On your account, go to "design" and "upload".

→ Browse to you file, select mm and upload your file to Shapeways. This may take a while, especially for larger models. In the meantime you can drink a coffee, check your e-mail or chase a rabbit.

Shapeways will automatically check the printability in your model for various materials. Check the printability for sandstone, once it is loaded. It may display some issues if your model is too thin, too large or has unstable parts that are likely to break (fig. 10 and fig. 11).

13 http://www.shapeways.com/materials/full-color-sandstone?li=nav



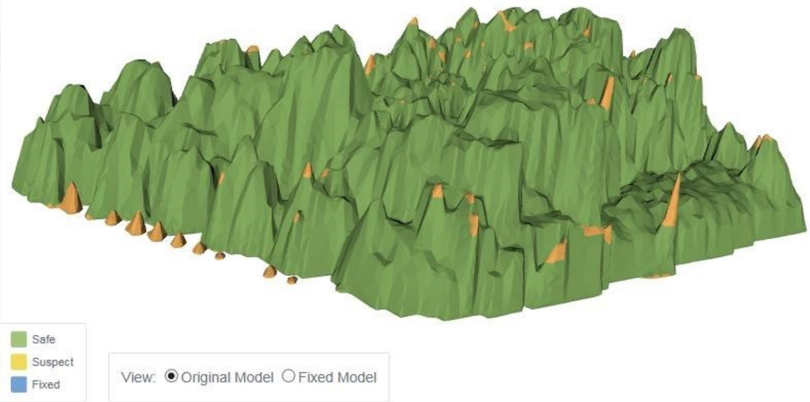


Figure 10) (left) and Figure 11) (right) Here Shapeways warns for "thin walls". As can be seen in the figure on the right, there are very thin protruding elements in the model that will most likely break.

If your model is deemed printable for sandstone, you can go ahead and order it – if you're willing to pay for it. You can also try to scale it down or make it thinner to reduce printing costs, but this may go at the expense of detail in the landscape and model strength! The printer has a maximum size of feature it can print in every material. Refer to the Shapeways Materials Guide to check whether it still makes sense to scale down the model.

Part V: Adding color using UV mapping in Blender

Not all 3D printers can print color according to a specified color file. Shapeways printers and the ZCorp printer at the Protospace FabLab in Utrecht[14] can do this and require that the 3D provided with a color map in .jpg or .png. We will use .png since it is a lossless compression file type. For the color map we will use the additional data layer we created earlier in ArcGIS and exported to .png.

However, printing color from a 2D .png file onto a 3D object comes with inherent problems. We cannot assume that the printer will know which color pixel corresponds to which surface polygon on the 3D object! To create a color model interpretable by a 3D printer we need to use a technique called UV mapping. This involves “unwrapping” the 3d model. You can think of unwrapping as spreading out all the polygons in a flat surface as displayed in fig. 12.

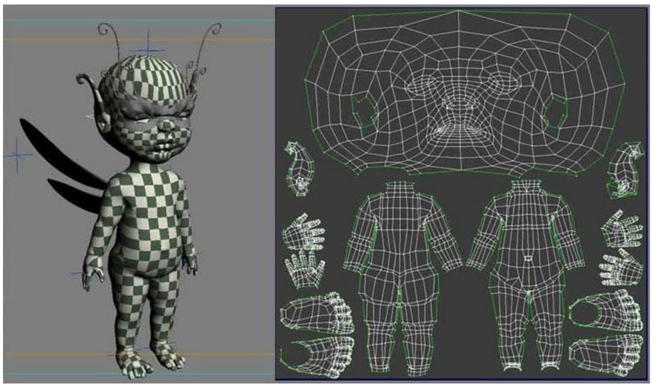


Figure 12) UV mapping procedure in Blender.
Source: www.blenderartists.org

Here we only want to use the top surface of the model to unwrap (the walls and bottom do not need any specific color). This is not easy for beginners, so be sure to follow the process below very strictly!

→ Divide the Blender view into two by grabbing the  icon at the top right and dragging it down. Then divide the top window into two similarly. It should look like fig 13.

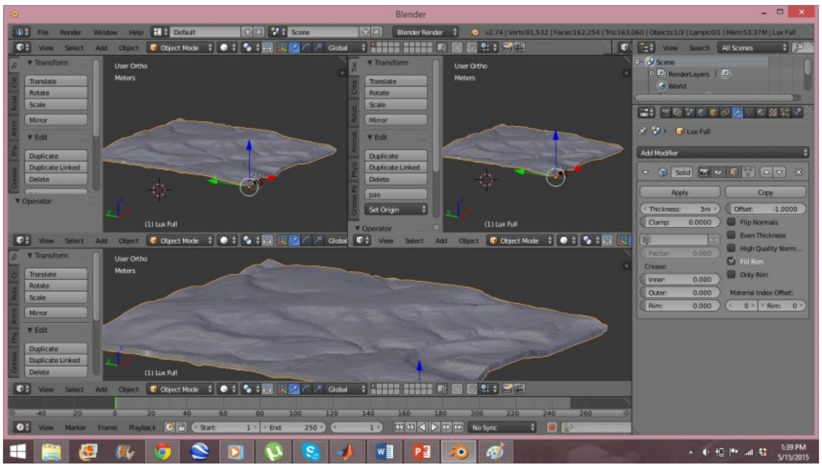


Figure 13) Initialization of UV mapping procedure in Blender.

14 http://protospace.nl/

Now, in each window we will initiate another sub process of the UV mapping procedure. We will unwrap the object from the bottom window into the top left window. From there we will export it to .png. We will manipulate it outside of Blender using image processing programs like Photoshop, GIMP or even just Paint. Then, in the top right window we will specify from which files Blender should generate a colored surface texture for the object.

→ Set the bottom window as in fig. 14: Switch from object mode to edit mode.

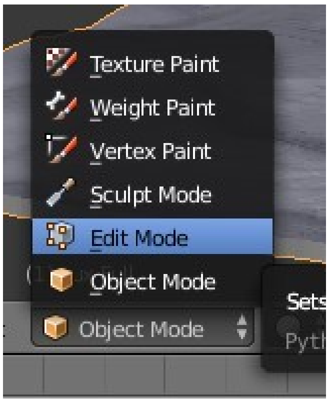


Figure 14) Switch into edit mode

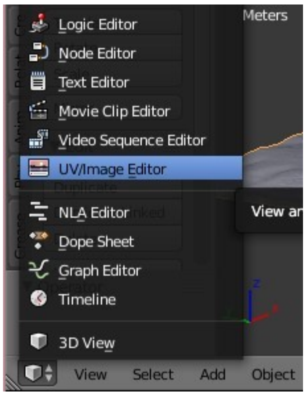


Figure 15) Set top left window to UV/Image editor

→ Using the numpad keys, set the view to Top Ortho using 7. This will set the view to a rectangular view of the top – this ensures that we will unwrap only the top of the plane and the color will be applied to the top properly. If the view is somehow incorrect, use 5 to switch between Ortho and Perspective, and the 7 to switch to top view.

→ In the top left window, select the cube and set the editor type to UV/image editor (fig. 15)

→ In the top right screen, set the editor type to node editor and on the top bar select “Cycles Render” (fig. 16).

Figure 16) Set the right window to node editor and Cycles Render.

We can now initiate the UV mapping.

→ In the bottom screen, go to the left-hand toolbar, and select the Shading Tab. Browse down to UV Mapping and select Unwrap. Select 'Unwrap project from View" (fig. 17).

An orange rectangle should now appear in the top left screen! If it's not a rectangle, make sure your view is set to Top Ortho.

→ In the top left screen, click the UVs tab and Export the UV layer (fig. 18). Save it as a .png.

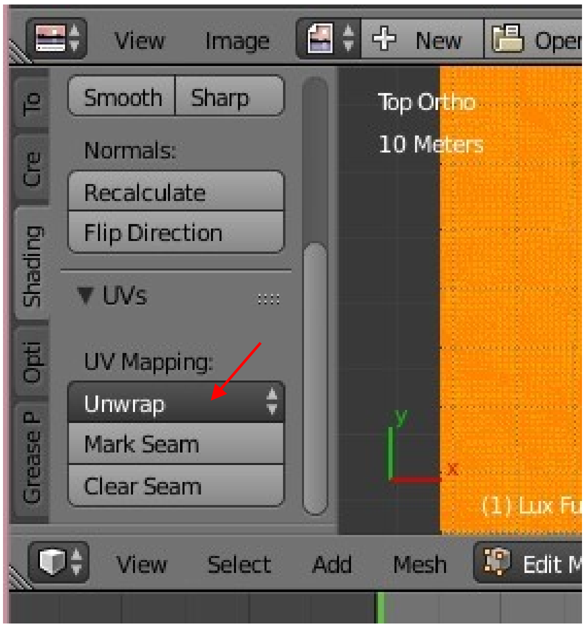


Figure 17) Unwrapping the 3D model.

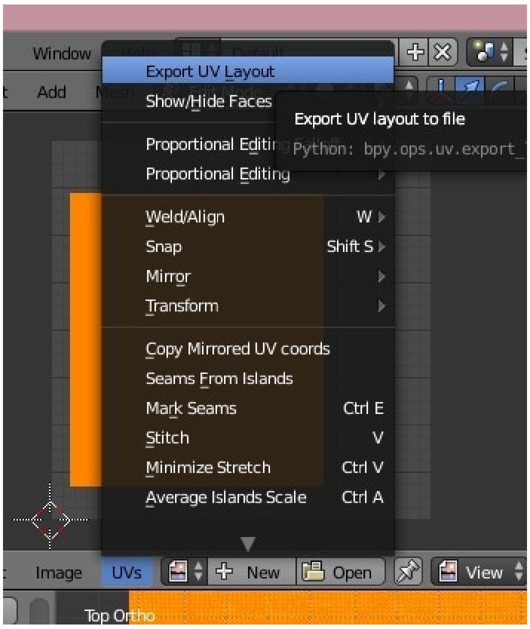


Figure 18) Exporting the UV Layout.

Now we leave Blender for a bit.

→ Open the .png file created in this step in an image processing program. I will explain the procedure for Paint (but GIMP or Photoshop is easier since they already work with layers).

→ The .png should feature a black rectangle. This represents the object's surface. We need to overlap our data layer to this rectangle exactly! Open the data layer .png in another Paint window.

→ Flip the data layer .png image vertically (ArcGIS and Blender save files differently). Then, we need to select it exactly and copy it to the window containing the UV image with the black rectangle. It may be wise at this point to zoom in and set a transparency for the data layer overlay just for now, it makes the fitting to the rectangle a bit easier. Then reset the transparency and save the changes to the UV map .png.

We now have a UV map that contains color. Now we need to associate it with the object again. We need to apply the UV map as a texture on the surface of the terrain object. In order to do this, we need to tell Blender that the object is made of a “Material” to which we will assign a texture.

→ Go to the Materials tab in the right hand toolbar. Check if the terrain object is specified and then create a new material. Give a name. Leave default settings and hit enter when you’ve typed a name (fig. 19). Some nodes will appear in the node editor representing your material (fig. 20). We will give the material a texture specified by the UV map.

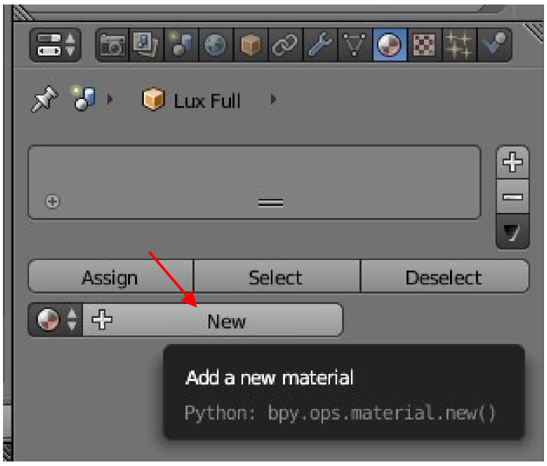


Figure 19) Creating a new material.

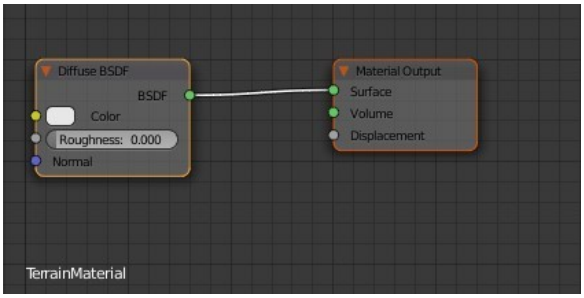


Figure 20) Two nodes appear in the top right window.

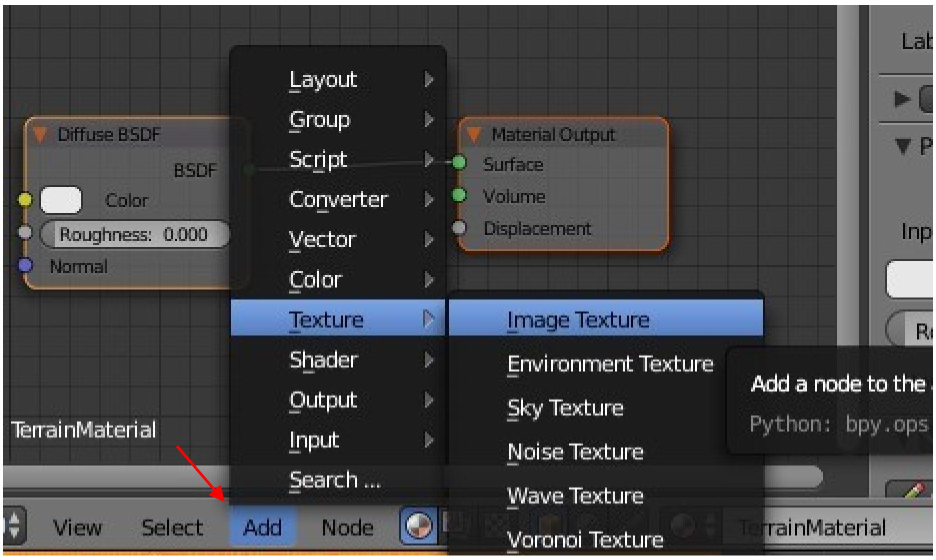


Figure 21) Adding texture to a material.

→ In the top right window Hit *Add* > *Texture* > *Image texture* (fig. 21).

→ The image texture node will have an "Open" button. Use it to browse to your UV map .png file and open it. Now connect the yellow dots on the Image texture node and Diffuse BSDF node like in fig. 22:

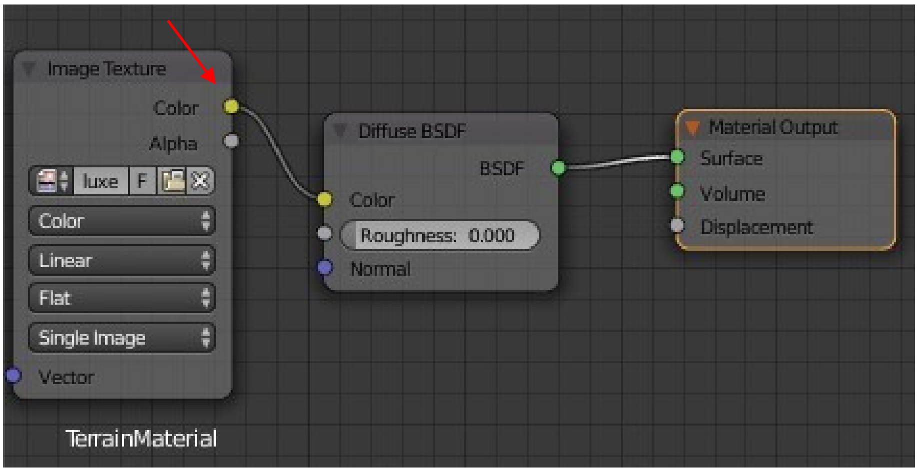


Figure 22) Loading your UV map as a texture.

Now the object has a color!

→ To see it, switch back to object mode in the bottom window, and in the dropdown menu next to object mode, select Material (see fig. 23).

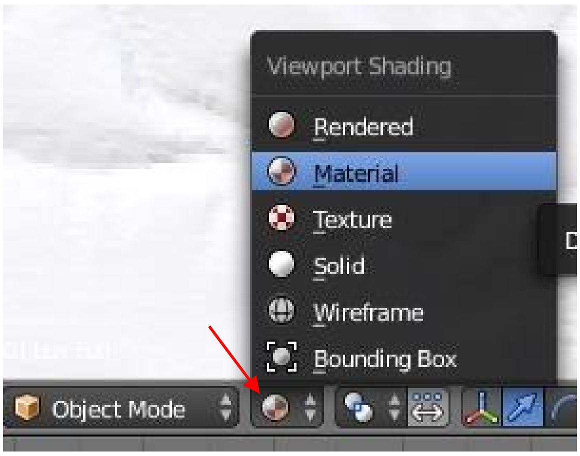


Figure 23) Making the image texture visible.

You will now see your 3D model with the proper colors!

Pan and turn the 3D object using the numpad keys and check for mismatches. Figures 24 to 27 show examples of properly rendered colored 3D objects.

If there is any mismatch between the color map and the height model, this may be due to the following reasons:

**   You may have forgotten to rotate the data layer before overlaying it on the UV map. Adapt the UV map in Paint.*

**   Improper overlaying of the data layer onto the UV map (be more precise). Adapt the UV map in Paint.*

**   If the color layer is much smaller or larger than the object itself, you have probably rescaled the model in between generating the UV map using unwrapping and applying it. Begin again from the Unwrapping part.*

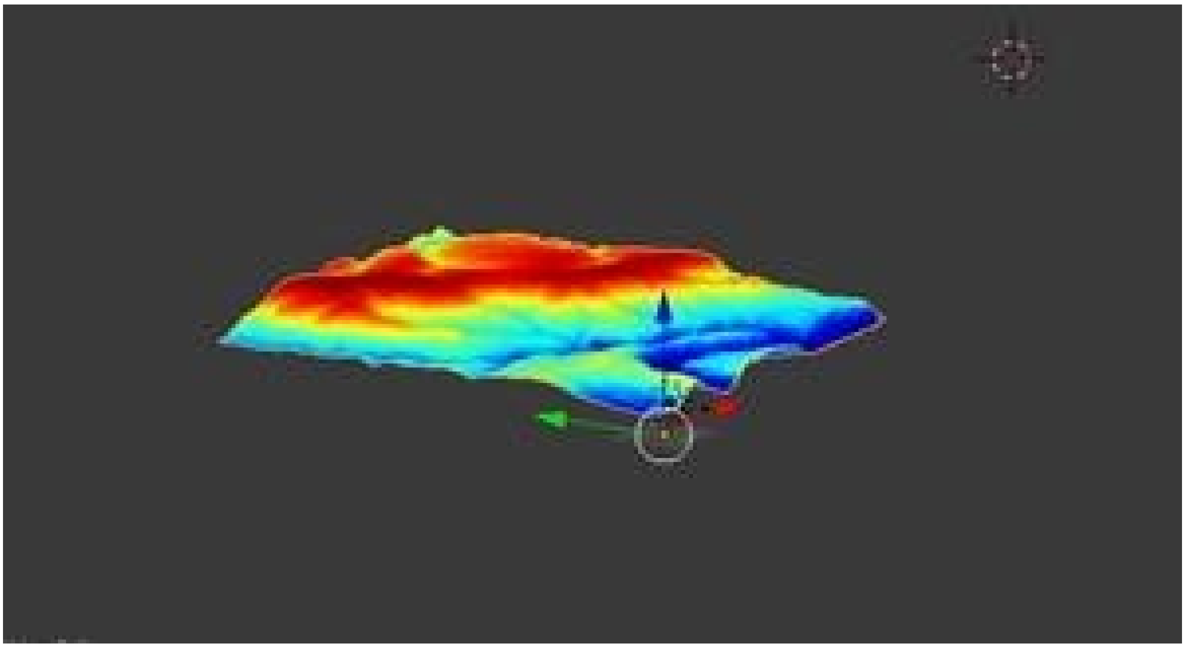


Figure 24) A fieldwork area of the University of Amsterdam in Luxembourg.

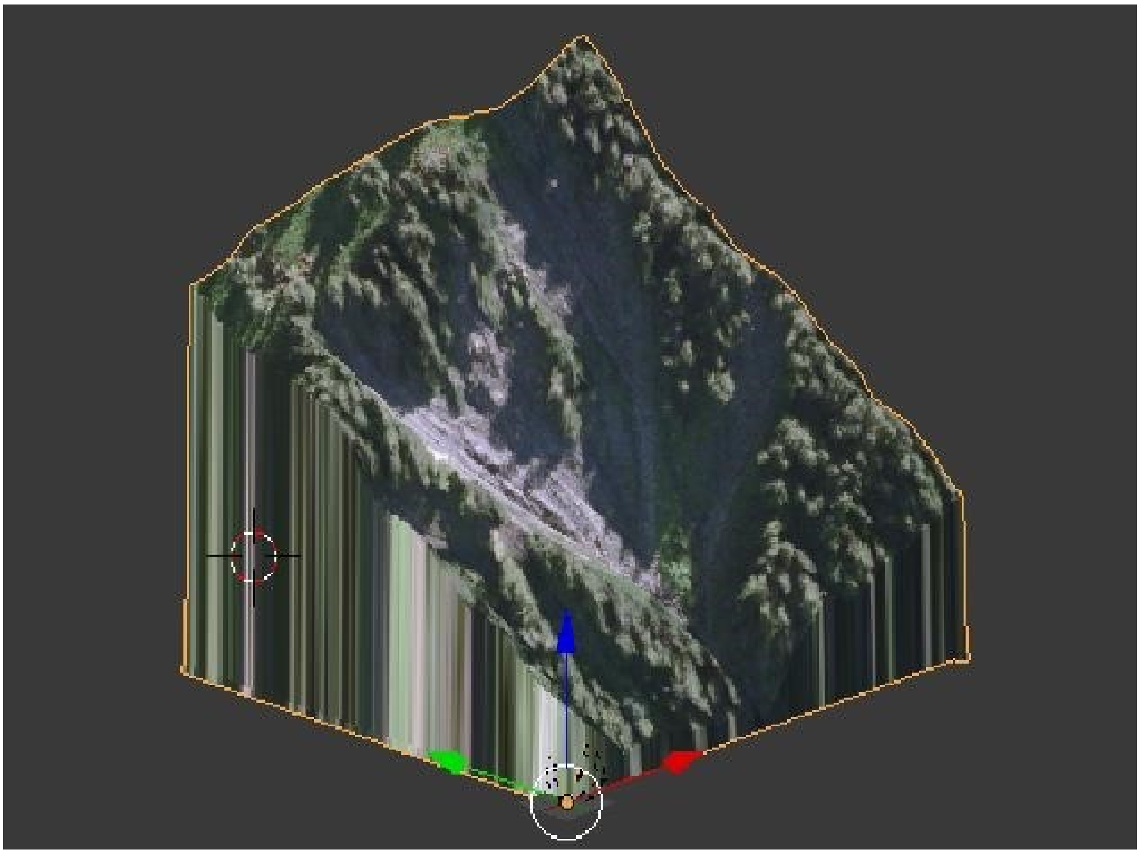


Figure 25) A recent mass movement event near Au, Vorarlberg, Austria with orthophoto overlay.

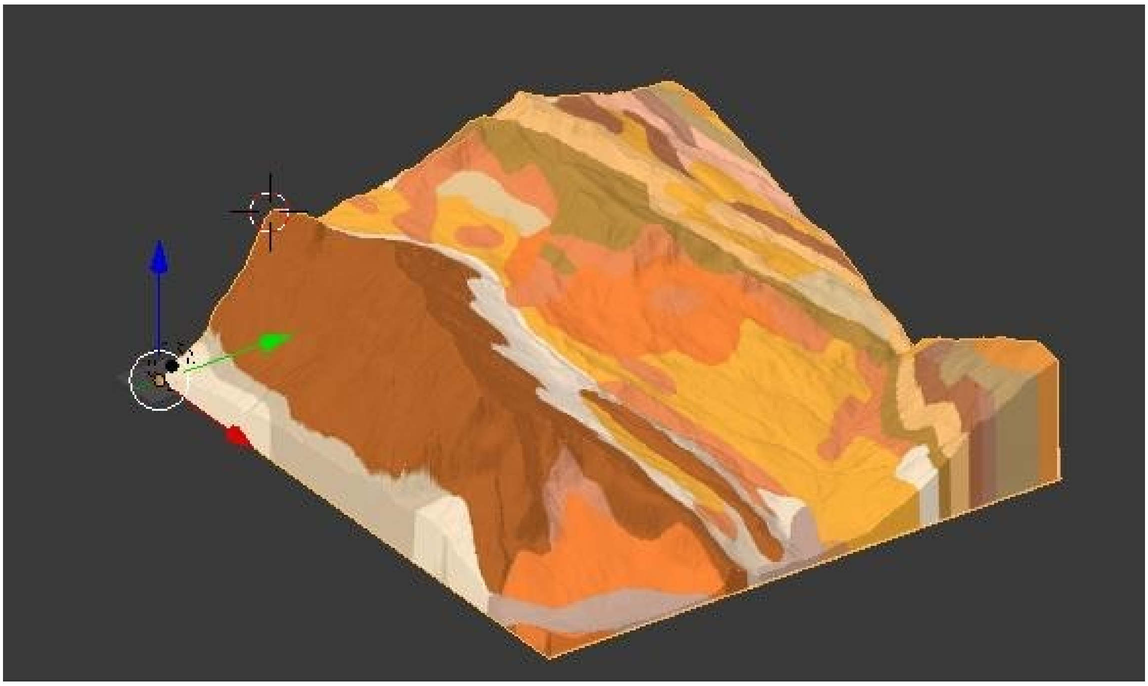


Figure 26) The University of Amsterdam fieldwork area in the Au region, Vorarlberg Austria, with geological units overlay.

Figure 27) Legend to the geological units represented in fig. 26.

→ Now, export the model to a .stl, .3ds or .x3d file (depending on which 3D printer you want to use) and give it the EXACT same name as the UV map .png!

→ To check how it worked out you can put the 3d model of the DEM in .x3d extension and the .png UV map in a zip. Make sure the zip has the same name as both the .x3d and the .png file and load to Shapeways for final checks of the model's printability.

→ It is also a good idea to save your Blender environment as a .blend file so that you can access it again easily: *File > Save.*

Part VI: Fixing issues with color mapping in MeshLab

As we have noticed, the UV mapping and export procedure in Blender sometimes does not save the link between the 3D model file (.x3d / .obj ,etc.) and the UV map (.png). This causes the model to display without color in the Shapeways preview. We have found a workaround for this issue using the freely available program MeshLab, although there may be better solutions by now for this problem. The solution involves importing the 3D model and UV map in MeshLab (http://meshlab.sourceforge.net/) and assigning the UV map to the model file.

- ➔ Export your 3D model as a .obj file from Blender and make sure the UV color map in .png is located in the same directory as this export.
- ➔ Import mesh in MeshLab.
- ➔ Browse to Filter > Texture > Set Texture.
- ➔ In the window that appears you need to type the name of your .png that has to be located in the same directory as your mesh.
- ➔ To check if your texture is applied correctly click “Render > Show UV Tex Param”. You should see a UV layout with your texture on it.
- ➔ Export the model as a .ply file under “Export”.
- ➔ Create a New document under “File”.
- ➔ Import the .ply file you just created. (You should see the texture on the object as you move it about in the MeshLab view).
- ➔ Export as an .x3d file with only the option "Wedge>Text Coord" selected under export settings.
- ➔ Zip the .x3d file with the .png texture created earlier and make sure they have the same name.

Part VII: Printing your project

Once you've loaded the model to Shapeways you'll have an idea of the printability of your final object and the costs associated with it. If the costs of the model are too high, you can try to scale the model down to a smaller size. This will go at the expense of the detail and size of the 3D model. An alternative is decreasing the wall thickness, but this may make the model too fragile.

Ordering the model directly from Shapeways is a very safe option since Shapeways offers additional checks before printing and finishing. It does mean however that the model will have to be shipped from America. Another option is to check whether a 3D printer that is capable of printing full colour sandstone is located near you through 3D Hubs https://www.3dhubs.com/. 3D Hubs is a network for designers and printer owners. You can send the job to any printer you wish and discuss your project with the owner of the printer.

Probably the most interesting option is to visit a FabLab such as ProtoSpace in Utrecht, the Netherlands; http://www.protospace.nl/. Here you can reserve and operate a ZCorp 3D printer yourself. This printer can print in full colour sandstone. Moreover, these FabLabs often have crew to help you get familiar with the machines they have available.

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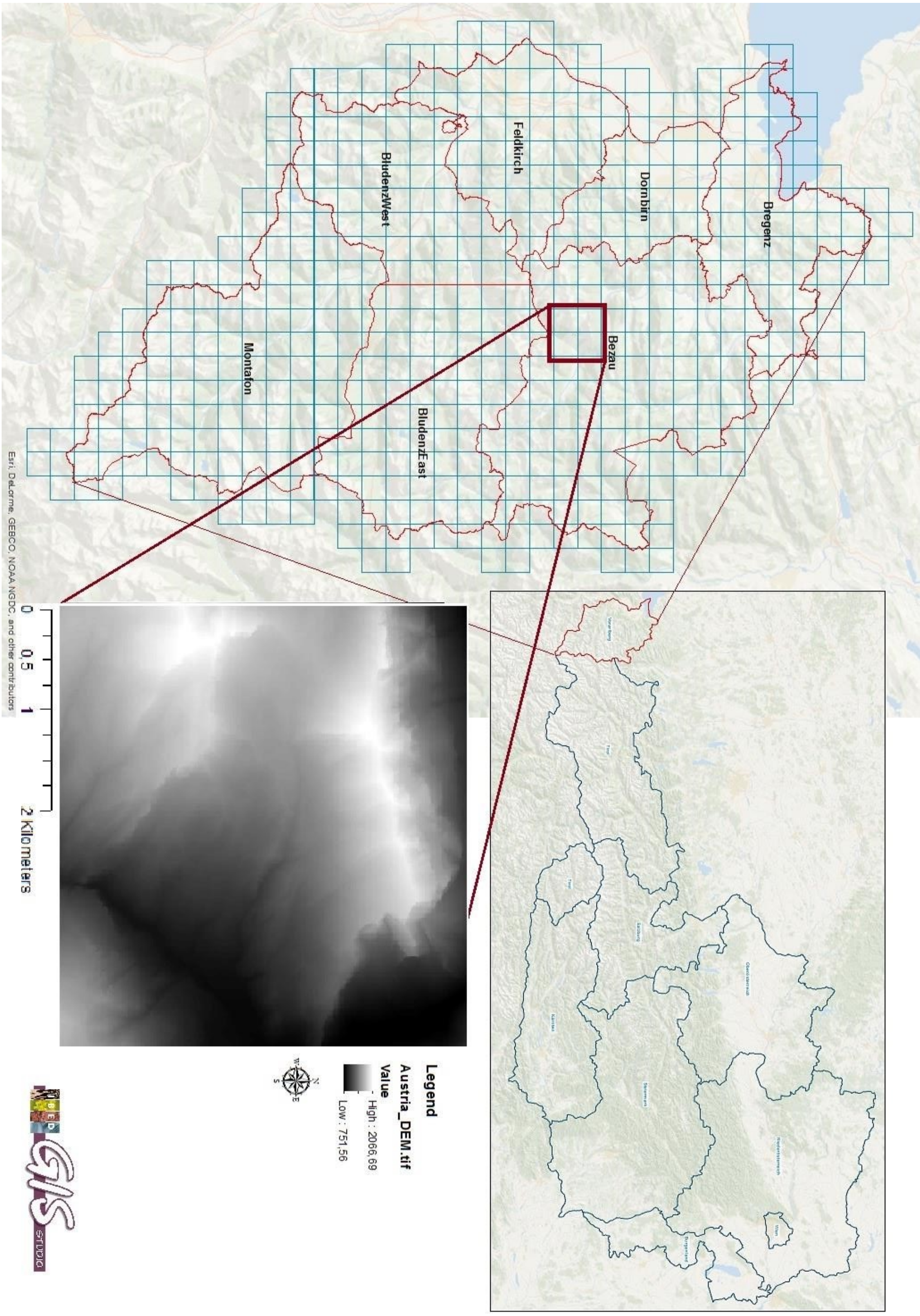
Addendum: Location of the study area



The digital elevation model (DEM) used as example was derived from 4 .las tiles containing LiDAR data of the terrain of the Vorarlberg province in Austria. Data was obtained from the UvA Geoportal: http://geodata.science.uva.nl:8080/geoportal/catalog/main/home.page.